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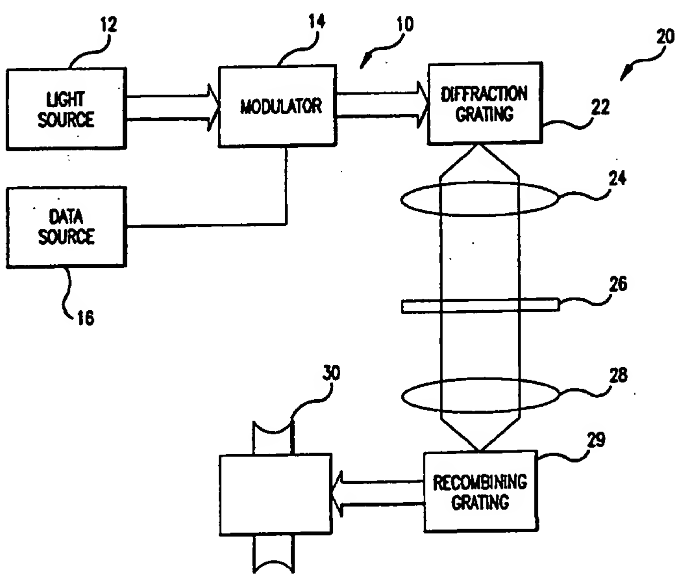

(57) Abstract

Methods and apparati for spatially encoding and decoding spread spectrum communication signals using broad band light sources are disclosed. The encoding algorithms involve the use of orthogonal spatial wavelets, which are preferably discrete attenuation functions of light from different sources so that the discrete attenuation function is imposed upon the spectrum of the light source. The function may be used either merely for providing an encoded channel or by providing a second mask that may be, for example, the complement of the discrete attenuation function so that the light beam is discrete with the first attenuation function.

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HIGH CAPACITY SPREAD SPECTRUM OPTICAL COMMUNICATIONS SYSTEM

Background of the Invention

Area of the Invention

This invention relates to spread spectrum communications systems and more particularly to optical spread spectrum communications systems.

Description of the Prior Art

Over the last two decades, optical communications over fiber optics have come increasingly into use for transmission of large quantities of data. Although initially, such fiber systems used narrow bandwidth systems such as those using laser light for communications, attempts have been made to increase system capacities. For example, in prior art systems, wavelength (frequency) division multiplexing has been accomplished by modulating a plurality of lasers at different frequencies and transmitting the modulated light from the various different lasers over the same fiber. Still further, various forms of time domain multiplexing have been done over digital fiber networks.

There have been a few proposals to provide digital optical networks using spread spectrum communications. These are set forth in the following papers and presentations: "Coherent Ultrashort Light Pulse Code-Division Multiple Access Communication Systems", Journal of Lightwave Technology, Vol. 8, No. 3, March 1990; L. Nguyen, B. Aazhang, J.F. Young "Optical CDMA with Spectral Encoding and Bipolar Codes", Proc. 29th Annual Conf. Information Sciences and Systems (Johns Hopkins University, March 22-24, 1995); N.B. Mandayan, B. Aazhang, "An Adaptive Single-user Detector for Optical Code Division Multiple Access Systems," Proc. 28th Annual Conf. Information Sciences and Systems, (Princeton University NJ March 16-18 1994) M. Brandt-Pearce, B. Aazhang, "Performance of Multiuser Detection for Optical Spectral Amplitude CDMA System", Proc. 27th Annual Conf. Information Sciences and Systems (Johns Hopkins University March 24-26 1993) p. 308-11; N.B. Mandayam, B. Aazhang "Generalized Sensitivity Analysis for Optical Code Division Multiple Access Systems" Proc. (same) p. 302-07; M. Brandt-Pearce, B. Aazhang "Optical Spectral Amplitude Code Division Multiple Access System" Proc. International Symposium on Information Theory, San Antonio Tx p. 379 Jan. 17-22, 1993; M. Brandt-Pearce et al. "Performance Analysis of Single-user and Multiuser Detectors for Optical Code Division Multiple Access Communications," IEEE Transactions on Communications, Vol.

Com-43 No. 3 1995; A. Pasasakellariou et al. "Code Design for Interference Suppression in CDMA Systems with Continuous Phase Modulation" Proc. 29th Annual Conf. Information Sciences and Systems, Johns Hopkins U. Md. 1995; and "High Capacity Optical CDMA Communications Networks presented July 1994 at the assignee of this application; A Semiclassical Analysis of Optical Code Division Multiple Access, D. Brady and S. Verdu, IEEE Transactions on Communications, Vol. 39, No. 1, January 1991, pp. 85-93; W. C. Wong et al. "Synchronous vs. Asynchronous CDMA for Fiber Optic LANS Using Optical Signal Processing", Nov. 1989, pp. 1012-1016; and the following U.S. Patents, Nos. 5,519,526 to Chan et al.; 4,703,474 to Foschini et al.; 5,289,299 to Paek et al.; 5,499,236 to Giallorenzi et al.; 5,410,147 to Riza et al.; and 5,438,440 to Paek et al.

In such prior art CDMA designs, however, there are severe drawbacks in the number of simultaneous users that the system can support. In particular, to efficiently use CDMA in optical communications, a large number of orthogonal codes must be used for providing the various coded channels. Preferably, it is desirable to have several hundreds or more such coded channels in a network. However, in optical communication a drawback of using a large number of codes is that this raises the effective noise floor in the system. In CDMA, each uniquely coded channel constitutes noise for the other channels and as the number of channels increases, this noise level increases dramatically.

Various systems have been tried to increase the number of channels. For example U.S. Patent No. 5,499,236 proposes using synchronous transmission to reduce the noise and using pseudo noise codes that modulate the data to spread the data spectrum. However, such pseudo noise codes are not orthogonal and the spreading is in the electrical domain. Further, the requirement of synchronization requires a master station with a precise reference clock and signaling of time information back to the transmitters. U.S. Patent No. 4,703,474 proposes combining spread spectrum techniques in the electrical domain with wavelength (frequency) division multiplexing in the optical domain. Here, pseudo-noise (PN) codes are used in the time domain and thus the system suffers the same problem as U.S. Patent No. 5,499,236. In addition, such a system requires complex time and frequency sweeps for acquisition of signal. U.S. Patent No. 5,438,440 suggests the use of a monochromatic light signal and a two-dimensional spatial digital encoder; i.e., a bit in the mask pattern is either fully transparent or fully opaque. Although such two dimensional spatial encoding improves the number of users the network can support relative to other prior art, it requires very complicated holographic detection systems. Using holographic detection, it is difficult to change the receive hologram so that if stations in a optical spread spectrum network are

removed from the network for maintenance or other reasons, the receive code cannot be readily reassigned to a different node, lowering overall efficiency.

One proposal has been to use bipolar digital codes as described in "Optical CDMA with Spectral Encoding and Bipolar Codes" cited above. In these bipolar digital codes, bipolar Walsh or Gold codes of length N are generated for a transmitter code. For a given code U, the complement U* is also generated and the code and the complement are concatenated together as U⊕U* to form an encoding code for first state. This code is embedded in the mask along an axis with for example one state in the digital code for a cell being implemented as a transparent area and zeros represented by an opaque area in the mask. In this system, a broad band light source is dispersed with a dispersion grating, collimated with a collimating lens, passed through the mask for spatial encoding so that the axis that the light is spread is arranged along the axis of the code, focused back on a recombining grating, and then provided to the modulator. A second, almost identical encoder is also provided for encoding light from the same light source with the complementary code U*⊕U, which encoded light is also provided to the modulator. Based upon input data or some other information source, the modulator selects between the encoded spectrum from the two different sources to provide an encoded, modulated spread spectrum with U⊕U* representing a data bit "one" and U*⊕U representing a data bit "zero." One mask can be used to generate both codes (i.e., U⊕U* and U*⊕U) by stacking the two codes on the same mask pattern. Alternatively a reflecting mask may be used to generate the two codes for the modulator.

Decoding according to this technique requires transmission of the two codes (U⊕U* and U*⊕U) on different channels and then each of the codes is passed through separate matched filter for both U⊕U* and U*⊕U. The output of the matched filters for each of the codes is then supplied to optical adders and then to photodetectors in a differential arrangement.

It is believed, however, that this technique using bipolar, concatenated codes and their complements will not permit less than an optimal number of users in a real life system as the interference from each of the users is believed to be high. Further, the transmitting of the two codes in separate, recoverable channels imposes costs on the system and can also result in different path delays and transmit channel mismatch.

Therefore, it is a first object of the invention of having a spread spectrum communication system where the number of users is maximized without raising interference unduly. It is a second object of the invention to provide a system providing a relatively

simple system for encoding and decoding the light but efficiently using the entire spectrum available. It is yet a third object of the invention to provide a spread spectrum communication system having codes that may be readily reassigned to other transmitters in the network.

Summary of the Invention

These and other objects are obtained by a using a novel spatial encoder with binary or analog encoding and a novel receiver. In particular, a wideband light source is modulated with the data or other information to be transmitted. The modulated light beam is then dispersed through for example a diffraction grating and then passed through a spatial spectrum coding mask. Preferably, the spatial coding mask is orthogonal to all other codes for other nodes on the network. The dispersed frequencies of the encoded modulated light beam are then recombined to provide a modulated, encoded spread spectrum optical signal for injection into an optical fiber.

Recovery of the transmitted signal is through the use of a special, matched filter. At any receiver, a beam splitter diverts part of the beam in the fiber through a diffraction grating to spatially separate the spectrum of the light in the fiber. The spatially spread signal, potentially comprising a plurality of spread spectrum optical communication systems is passed through a novel receiver, thereby providing signal recovery. This receiver can be implemented in a number of ways. Three receiving structures are disclosed in this patent application depending on the proposed coding scheme.

In one embodiment, the codes are binary orthogonal codes such as Walsh codes. The spatially spread light will pass through two decoding masks. One decoding mask is the same as the encoder mask while the other decoding mask is the bit-wise complement of the encoder mask. The spatially spread decoded light signals are combined, and differentially detected.

In another embodiment, the spatially spread light can be detected by an array of detectors. Each detector in the array measures the light power of the corresponding optically spread wave length. The array of electrical signals will then be processed by a DSP. The digital processing comprises of multiplying the signal from each detector in the array by positive or negative one depending on whether the encoder mask bit is a one (transparent) or a zero (opaque). The resulted bit products are then summed before thresholding for data recovery. This digital processing corresponds to multiplying the signal from individual detector in the array by the corresponding bit in the Hadamard code which is the bipolar

version of the Walsh encoder code.

The coding further includes the use of analog codes. By analog coding what is means is that the spatial encoder uses variable opacity masks as opposed to digital coding (i.e., where the spatial encoder uses masks with cells that are either transparent or opaque). The code preferably should use one of a set of unique, orthogonal wavelet functions such as cosine and/or sine waves, rectangular waves or Chebishev polynomials. The orthogonal wavelets are of course discrete functions as opposed to continuous functions due to the fact that the masks are not continuous but comprise a plurality of cells.

In this embodiment, the wavelets are quantized or discrete spatial sine waves of various harmonic frequencies. This permits decoding to be done by using a spatial fourier transform on the detected spatially spread light pattern. The limit on the number of codes is only based upon the effects of using discrete as opposed to continuous harmonic sine waves and the resolution of the receiver.

Description of the Figures

Figure 1 is a block diagram of a first embodiment of an encoder according to the present invention.

Figure 2 is a block diagram of a first embodiment of a decoder according to the present invention.

Figure 3 is a block diagram of a second embodiment of a decoder according to the present invention.

Figure 4 is a sketch of a liquid crystal mask for use in a third embodiment of an encoder according to the present invention.

Figures 5A, B and C are continuous representations of discrete transparency functions for the mask of Figure 4.

Figure 6 is a graphical representation of a fourier transform of light received from the fiber.

Figure 7 is a graphical representation of an encoder and a decoder according to a third embodiment of the invention.

Figure 8 is a graphical representation of mask and mask functions according to a third embodiment of the invention.

Detailed Description of the Preferred Embodiments

Figure 1 shows a first embodiment 10 of a CDMA modulator/encoder. A broadband light source 12, such as a SLD or Er-doped fiber source, is coupled to an optical modulator 14. The optical modulator modulates the light from the optical source 12 based upon data or other information from the data source 16, using, for example, keying or pulse code modulation.

The modulated broad beam light beam is then encoded by the encoder 20. The encoder 20 includes a diffraction grating 22 that spatially spreads the spectrum of the modulated light beam along an axis and then is collimated by a collimating lens 24 where the collimated beam is passed through the encoding mask 26. The encoded mask, as described below in detail, provides a spatially encoded, modulated spread spectrum beam that then is recollimated by a collimating lens 28 and combined back to a broad spectrum beam by a diffraction grating 29 for injection into the fiber 30, which may be an appropriate optical fiber.

Figure 2 shows a compatible decoder, which has two channels 50 and 51. Through a beam splitter 40 light from the fiber 30 containing a potential plurality of spread spectrum signals, two beams are provided. One incoming beam is spread spatially along an axis by a diffraction grating 52 and is then collimated by a collimating lens 54 before being passed through a detection mask 56. The receive masks 56 is identical to the encoding mask 26. The beam after being passed through the decoding mask 56 is passed through a collimating lens 58 and a diffraction grating 59 to remove the spatial spreading. The other incoming beam is also spread spatially by a diffraction grating 53 and is then collimated by a collimating lens 55 before being passed through a second decode mask 57. However, this second decode mask 57 is the bit-wise complement of the encoder mask 26. The beam, after being passed through the second decoding mask 57, is passed through the collimating lens 60 and a diffraction grating 61 to remove the spatial spreading. The output of the first decoder channel 50 may then be supplied to a photo detector 62 to convert the light into an electrical signal. Similarly, the output from decoder channel 51 is supplied to a photo detector 63 to convert the light into an electrical signal. The two electrical signals are then differenced by the back-to-back arrangement of the two detector diodes, 62 and 63 for being supplied to data and clock recovery hardware and/or software 64. The differential electrical signal is then detected for data recovery.

Figure 3 shows another embodiment of the decoder 70. In this embodiment, the beam is not split into two channels with two masks, but instead it is spread by the grating 71

and is collimated by a lens 72. The collimated light is then intercepted by an array of detectors 73. The number of detectors in the array is equal to the number of bits in the encoder mask. Each detector position corresponds to the encoder mask bit position. The detector signal from each detector in the array is multiplied by either "1" or "-1" depending on the corresponding encoder mask bit is a "transparent" or "opaque." The results of all the multiplier outputs are then summed. The sum is then compared with a threshold 75 for data recovery. This digital processing can be performed in discrete logic hardware or in a DSP 74 through software. It should be noted that in both embodiments of Figures 2 and 3 only one encoder mask is used for transmit and no concatenated code is required in contrast with prior art designs.

The coding masks 26, 56, 57 are preferably made of liquid crystal material as shown in Figure 4 divided into a plurality of cells A through L, with L an arbitrary integer and being the maximum permitted length of the code. The cells form a one dimensional array arranged along the axis 55 of spatial spectrum spreading caused by the diffraction gratings 22, 52. In one embodiment, the control of the cells is analog, meaning that the opacity of each cell is either infinitely adjustable or is adjustable in at least three or more separately controllable stages. Preferably a large number of finite stages, preferably sixty-four or greater levels of opacity should be used. In another embodiment, the control is binary, and Walsh code is used. These masks can be implemented by LCD pixel arrays or by photonic integrated circuit such as solid state amplifier array.

A preferred form of analog coding is using orthogonal wavelet functions. In an embodiment, the wavelet functions are discrete harmonic spatial sine waves (represented for purposes of illustration as continuous functions) as shown in Figure 5. The ordinate axis is the axis along which the frequencies of the beam are spread and the abscissa is the relative transparency of the beam passing through a cell. In particular, a first encoder mask transparency function shown in Figure 5. A at a first location may have a spatial frequency of 1 /L, where L is the number of cells. The mask of that first encoder is a discrete (as opposed to continuous) cosine wave in terms of transparency having one cycle over the frequency spectrum of L, such that the lowest and highest frequency portion of the encoded spectrum have the maximum intensity and the mid-range spectral frequencies have the lowest intensity. A second encoder mask may for example have a spatial frequency intensity mask of twice the frequency of the first encoder with two full cycles across the length of the encoder L of Figure 5B. Still further a third encoder may have a frequency three times the frequency of the first encoder as shown in Figure 5C. Other higher harmonics are preferably

used, and preferably to maximize the system throughput, the maximum number of codes should be over one hundred and preferably over several hundred.

The maximum number of harmonics or Walsh code bits (and therefore, the maximum number of codes) is limited only by the number of cells in the mask. For the analog mask, the number of different levels of opacity permitted in the mask, results in the quantization noise in the encoder. Alternatively, rather than using cosine waves, Chebishev polynomials could also be used as they are orthogonal with respect to each other.

Using cosine waves for the encoding function also permits an easier decoder design. In particular, if one takes the spatial Fourier transform of the received signal, the received signal can be separated through a spatial filter for the frequency of the desired signal and then that signal can be recovered. As a simple example, Figure 6, shows the Fourier transform of a signal received from a fiber where the separate encoded signals include 1/L, 2/L, 4/L and 8/L. Any one of these signals may be readily obtained by filtering for that particular spatial frequency in the frequency.

In a preferred third embodiment of the disclosed encoder, rather than pulse code modulate the data, an alternative method may be used for modulating using two codes as is shown in Figure 7A. In this embodiment of an encoder, the optical path for the spatially spread light source 102 is switched between a first mask 106 and a second mask 108 by a switcher 104 responsive to data from a data source 101, the first mask encoding the light to provide a digital "one" signal and the second mask encoding the light to provide a digital "zero" signal for the same code channel. The modulator switches the light path between two different encoder masks using one liquid crystal in a manner that is described in the same way as the binary mask receiver embodiment. The light from both masks is then summed by a summer 110 and then provided to the optical communications channel such as an optical fiber (not shown).

Receiving works in the converse manner as shown in Figure 7B. A decoder 120 receives light from the communications channel and generates the spatially spread spectrum of the received light with receiving input optics 122 through masks 124, 126 which are identical to the mask 106 and the mask 108 respectively. The light from the masks 124 and 126 is then provided to a differential receiver 128 in the manner described above in the binary receiver embodiment. The signal from the receiver 128 may then be processed by a digital signal processor 130 for recovery of the data.

Figure 8A shows one alternative embodiment of the masks appropriate for coding where two different masks are used for transmitting ones and zeros. In a first version, the

mask formed of L cells in a liquid crystal mask 150 is divided into four parts, 152, 154, 156 and 158. Parts 152 and 154 comprise L/2 cells each along a first linear array arranged along the axis of spreading of the spectrum on a first row to encode a "one" for this particular code channel and at a second column, cells 156 and 158 also comprise L/2 cells arranged along the same axis for encoding a "zero" for this same channel. Preferably, the discrete transparency functions for parts 152, 154 are the complements of each other such as shown in Figure 8B, where the ordinate represents spatial frequency and the abscissa represents intensity. For transmitting the other possibility (i.e. the zero), as shown in Figure 8C, the complements of the discrete intensity functions for parts 156 and 158 are reversed. In other words, the portion of the mask in section 152 is identical to the portion of the mask in 158 and the portion of the mask in 154 is identical to the portion of the mask in 156. In this embodiment, the codes for other.

In addition to having masks where the coding is complementary, it is also possible to provide coding where a first portion 152 of the mask is the orthogonal wave function and the second half is all opaque for a "zero" 154 and the second level, the first half 156 is all opaque and the second half is the same pattern as the first half 152 to make a "one." Alternatively, the first halves 152, 156 can be a first polynomial such as a sine wave and the second halves 154, 158 can be a second polynomial such as a Chebishev function.

Although specific embodiments of encoders and decoders according to embodiments of the invention are disclosed, other embodiments of the invention are also possible. For example, while discrete wavelet functions are used for encoding, it is possible to have masks that permit continuous functions for coding. For example, the masks may be formed photographically.

Furthermore, it should also be understood that all of the disclosed embodiments of encoders and decoders can also be applied to analog modulation of the optical signal.

Similarly, while only CDMA techniques have been described above, those of ordinary skill in the field will readily understand that depending upon system parameters the system may also be used with wavelength (frequency) division multiplexing and time division multiplexing. For example, different coding schemes may be used for different portions of the optical spectrum so that wavelength division multiplexing may be used. In addition, the codes may be shared on a time sharing basis to provide for time division multiplexing. Also, optical spatial (spatial) CDMA can be combined with time domain optical CDMA to increase the number of codes and the users in the network. In the

time domain spread spectrum embodiments, several users are provided with different time domain spread spectrum codes for encoding the data before the data is provided to the optical encoder. However, these users can share the same wavelength encoding schemes discussed above. Of course, at the decoder, once the received optical information is converted back into the electrical digital domain, the digital signal must be processed according to the time domain spread spectrum code to recover the desired transmitted information.

In addition to the various different possible types of combinations of multiplexing schemes that are possible, various network algorithms may also be implemented. For example, the codes for any one node may be assignable from one or more master nodes distributed throughout the network. Hence, when a node in a network comes on line, it requests a code or codes for encoding for selecting one of the possible spread spectrum channels over which to communicate. When that node leaves the network, the code that had been used by that particular node may be reassigned to a different node in the network. Various schema may be used for making such requests such as CSMA/CD technique or token passing on a permanently assigned channel. Alternatively, token passing techniques may be used for gaining codes for securing one of the code division channels.

In addition, the disclosed embodiments permit an increase in the number of simultaneous users. In particular, in prior art schema such as those discussed above, the maximum number of simultaneous users that are permitted for the same number of codes is $2^{N/2}$ where N is the maximum number of codes. However, in the disclosed embodiment, the maximum number of codes with holding everything else constant is 2^N. Thus, total system throughput is dramatically increased, thereby permitting a system throughput of at least one half of a terabit, with the total system throughput being determined by the maximum number of simultaneous users, and the users data rate.

Therefore, while several specific embodiments of the invention have been disclosed, it will be understood by those of skill in the field that many alternative embodiments are possible. Of course, the scope of the inventions disclosed should be measured by the claims.

I claim:

1. In an optical spread spectrum communication encoder for transmitting information over an optical fiber, the optical spread spectrum encoder comprising a broad beam light source, a spatial frequency diffractor for spatially spreading the spectrum of the beam of light along an axis, an encoder comprising a mask divided into a plurality of cells arranged along the axis for spatially optically encoding the spread spectrum beam passing through the mask with one of a plurality of orthogonal functions and a spatially spread spectrum recombiner for recombining the spatially spread spectrum of the light passed through the mask, wherein the improvement comprises:

   the opacity of each cell being one of at least three possible levels.

2. The encoder of claim 1, wherein the mask imposes a spatial spectrum on the light passing through the mask, the spatial spectrum being the spectrum of a discrete analog function.

3. The encoder of claim 1, wherein the wavelet defines the spatial spectrum of a discrete sine wave.

4. The encoder of claim 1, wherein the wavelet defines the spatial spectrum of a Chebishev polynomial.

5. The encoder of claim 1, wherein the encoder includes a data modulator for pulse code modulating the beam from the optical source before spatial spreading.

6. The encoder of claim 1, wherein the encoder includes a modulator and the mask includes two parts, a first part for encoding a first state into the spread spectrum beam and a second part for encoding a second state into the spread spectrum beam, both parts comprising a plurality of cells with each cell having one of at least three different levels of opacity.

7. The encoder of claim 6, wherein the first part of the mask defines a first wavelet on and the second part of the mask defines a second wavelet.

8. The encoder of claim 6, wherein the cells of the mask define at least thirty-two different levels of opacity.

9. The encoder of claim 8, wherein each part of the mask is divided into two subparts arranged along the axis, the first subpart of the first part includes the wavelet and the second subpart of the second part includes the complement wavelet.

10. The encoder of claim 9, wherein the wavelet is a sine wave.

11. The encoder of claim 9, wherein the wavelet is a Chebishev function.

12. In an optical spread spectrum communication system comprising a medium over which a plurality of code division multiple access optical signals are propagated from a plurality of different active encoders for different channels, each encoder comprising:

a broad spectrum optical source providing a light beam having a broad spectrum;

a spatial spectrum spreader spreading the spectrum of the light beam along an axis;

a mask having a plurality of cells arranged along the axis, each cell in the mask having a predetermined opacity to define a spread spectrum code in the spread spectrum light beam, the spread spectrum code being a discrete wavelet;

a spatial spectrum recombiner for recombining the spatially spread spectrum.

13. In the spread spectrum system of claim 12, wherein each wavelet for each encoder comprises a sine wave or a rectangular wave of a different spatial harmonic for each channel.

14. In the spread spectrum encoder of claim 12, wherein each wavelet for each encoder comprises a Chebishev function of a different order for each channel.

15. In the spread spectrum encoder of claim 12 wherein the mask is also used for modulating the light beam with information, the mask including a second plurality of cells arranged along the axis, each cell having a predetermined opacity to define a spread spectrum code in the spread spectrum light beam, the spread spectrum code being a second discrete wavelet.

16. In the spread spectrum encoder of claim 15, wherein the first and second discrete wavelets are the same.

17. In the spread spectrum encoder of claim 15, wherein the mask modulates a first state with the first discrete wavelet on a first portion of the spread spectrum and modulates a second state with the second discrete wavelet on a second portion of the spread spectrum.

18. In the spread spectrum encoder of claim 17, wherein the first discrete wavelet comprises a first function followed by the complement of the function arranged along the axis from the lowest to the highest frequency and the second wavelet comprises the complement of the first function followed by the first function arranged along the axis from the lowest to the highest frequency.

19. A method for spread spectrum communications over an optical fiber, the method comprising:

spreading the spectrum of a broad band light source along a first axis; selectively attenuating different portions of the spectrum to define a discrete analog spatial encoding function in the spectrum; and

combining the attenuated spectrum for transmission over an optical fiber.

20. The method of claim 19, wherein the selective attenuating further results in modulating the spectrum to have one of two states based upon information to be transmitted.

21. The method of claim 19, wherein the modulating comprises:

encoding a first discrete analog spatial encoding function in the spectrum for a first state; and

encoding a second discrete analog spatial encoding function in the spectrum for a second state.

22. A method of recovering a spatially encoded spread spectrum signal according to a spatially encoded discrete spectrum function from an optical fiber having a plurality of such spatially encoded signals, the method comprising:

diverting a portion of the light across the spectrum from the fiber;

spatially spreading the spectrum of the light along a first axis;

passing the spatially spread spectrum through a mask defining the spatially encoded discrete spectrum function to provide a filtered spectrum; and

detecting the data from the filtered spectrum.

23. The method of claim 22, wherein the encoded signal is modulated to have one of two states method further comprises:

filtering the spatially spread spectrum with the first discrete function and a second discrete function;

determining if the encoded signal is in the first state or the second state based upon detecting the light from both filters.

24. A method of communicating between a plurality of nodes on an optical spread spectrum communications network, a plurality of nodes comprising:

an encoder to encode light with information an optical spread spectrum encoder at a predetermined data rate to transmit the encoded information on a first spread spectrum channel;

a decoder to recover information encoded through optical spread spectrum communication, wherein the network capacity is at least 500 terabits.

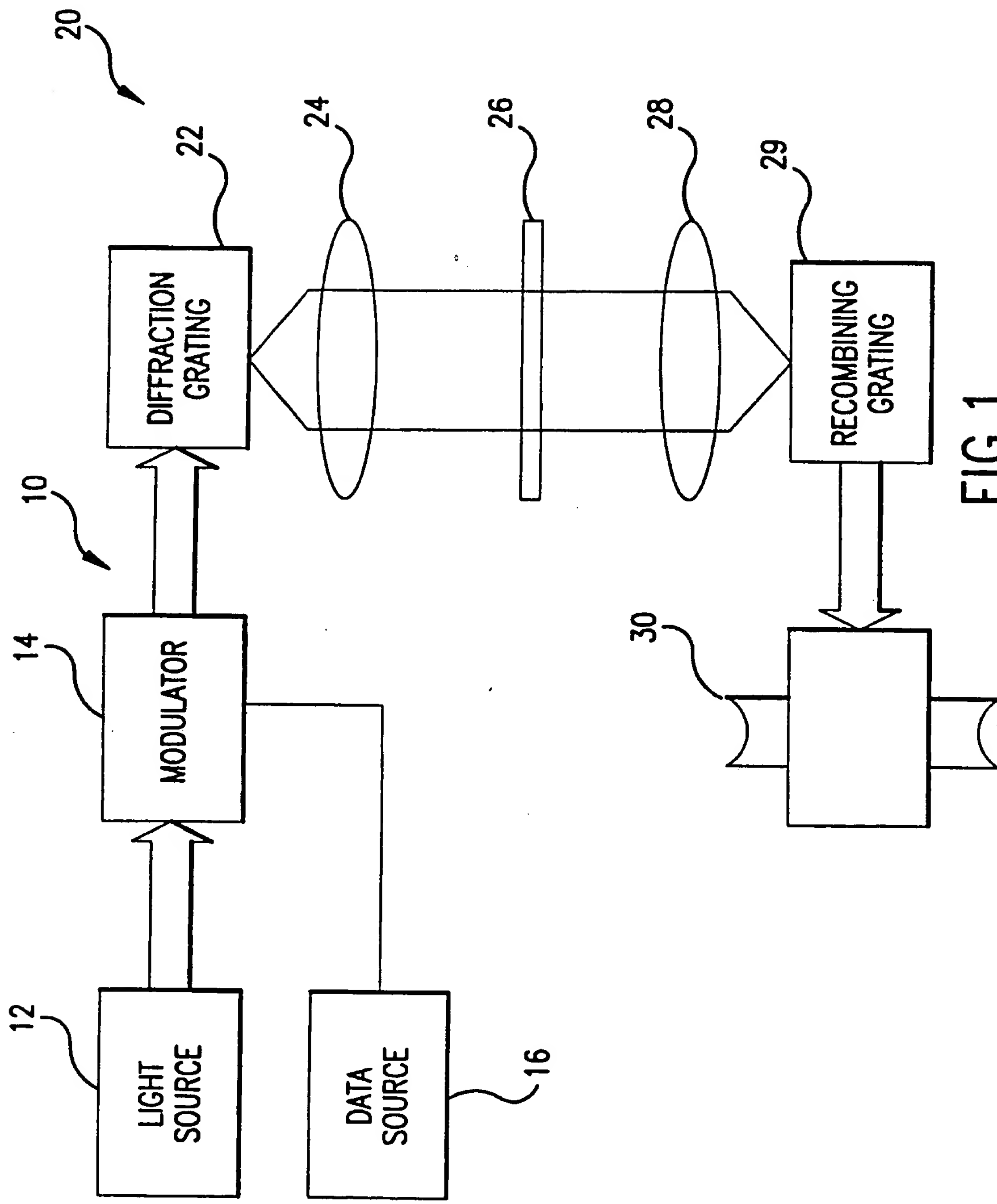
20
10
LIGHT SOURCE
12
MODULATOR
14
DATA SOURCE
16
DIFFRACTION GRATING
22
24
26
28
RECOMBINING GRATING
29
30

FIG. 1

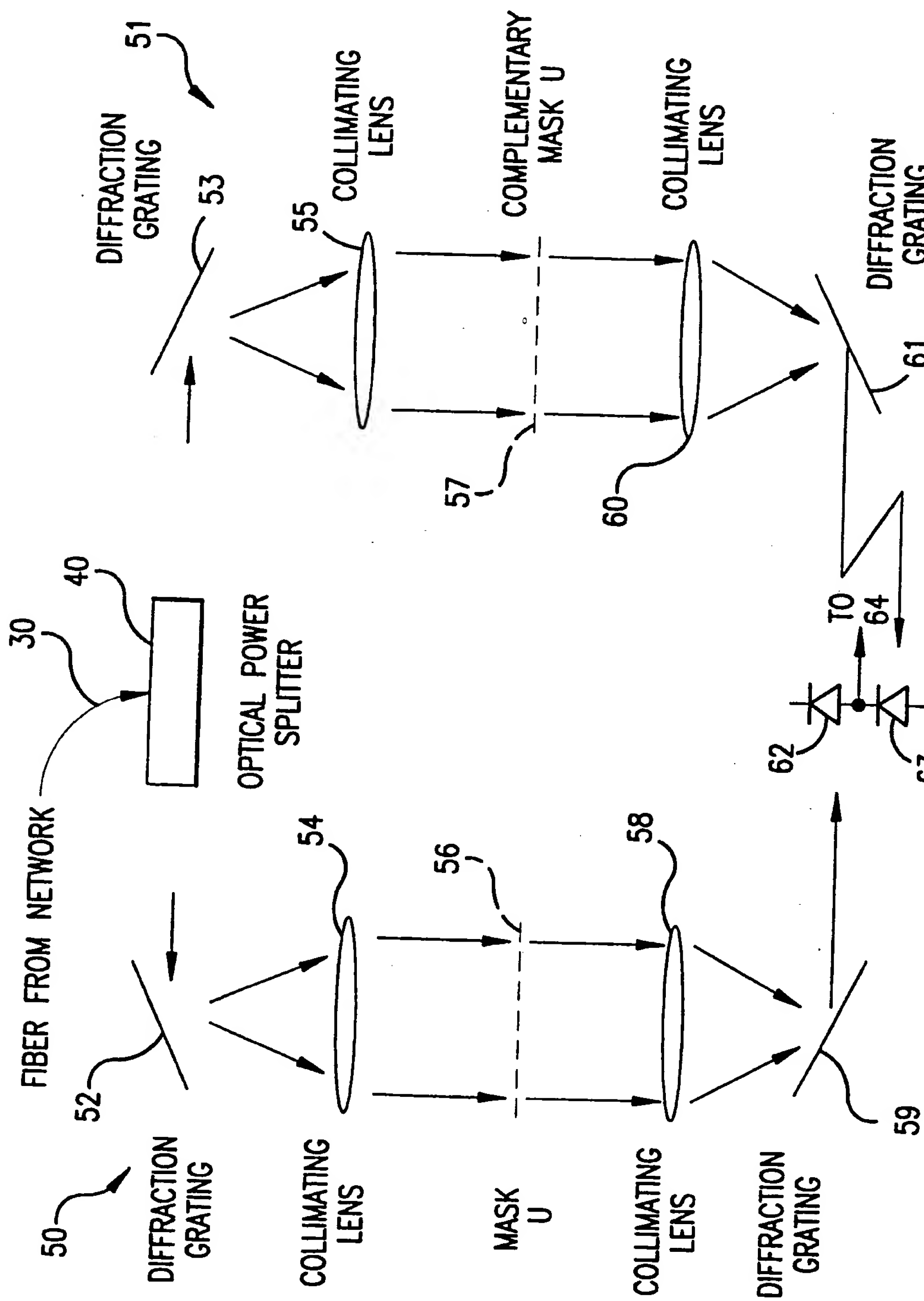
FIBER FROM NETWORK
30
40
OPTICAL POWER SPLITTER
50
51
DIFFRACTION GRATING
52
53
COLLIMATING LENS
54
55
MASK U
56
COMPLEMENTARY MASK U
57
COLLIMATING LENS
58
60
DIFFRACTION GRATING
59
61
62
63
TO 64

FIG.2

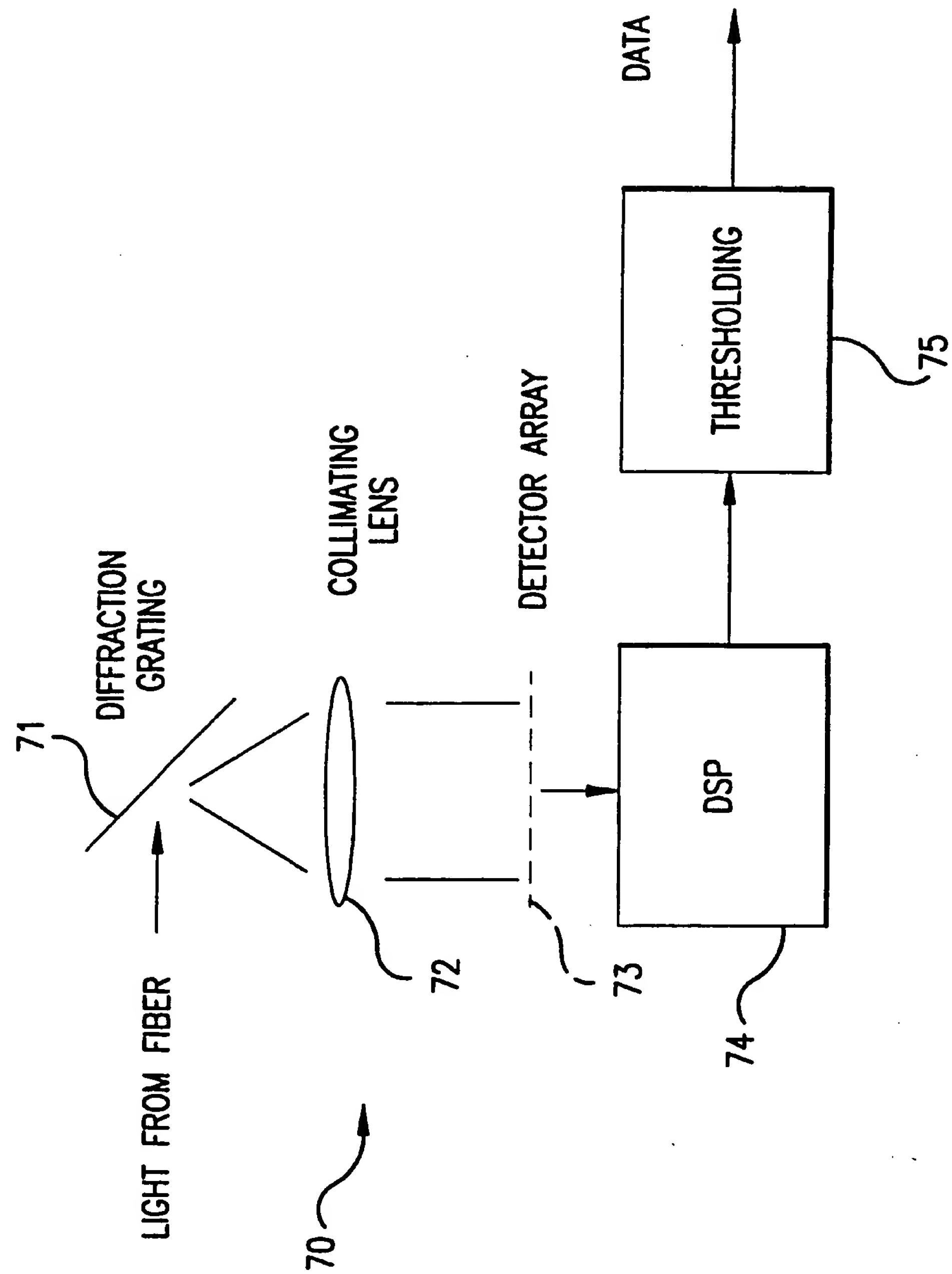
DATA
THRESHOLDING
75
COLLIMATING LENS
DETECTOR ARRAY
DIFFRACTION GRATING
71
DSP
LIGHT FROM FIBER
72
73
74
70

FIG.3

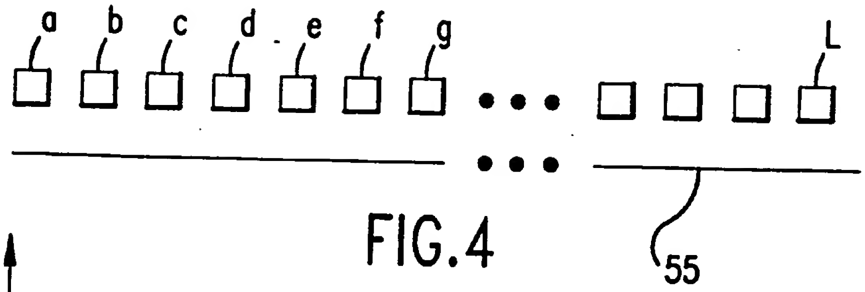

FIG.4

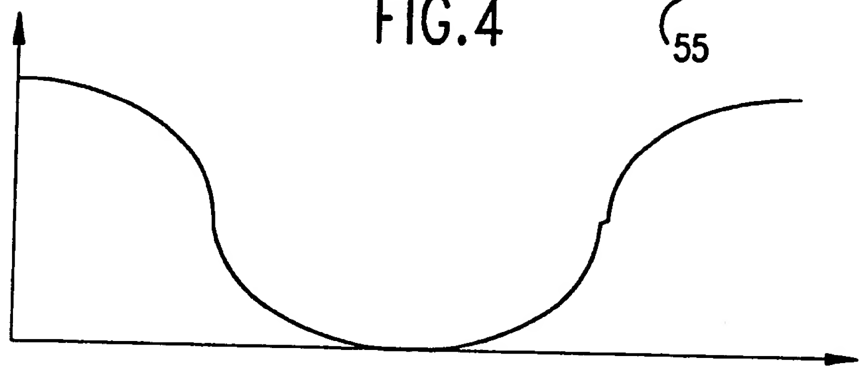

FIG.5A

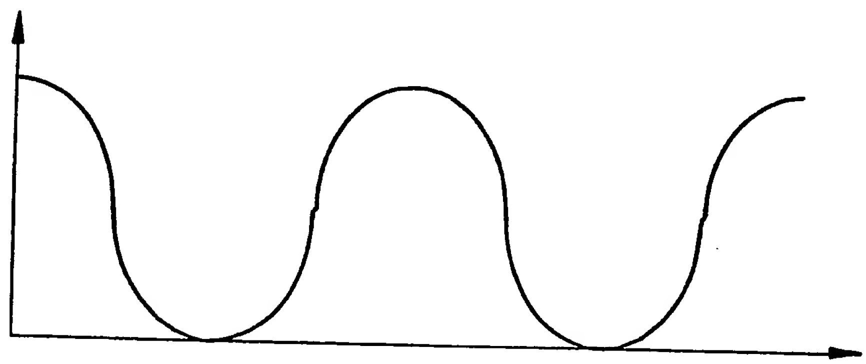

FIG.5B

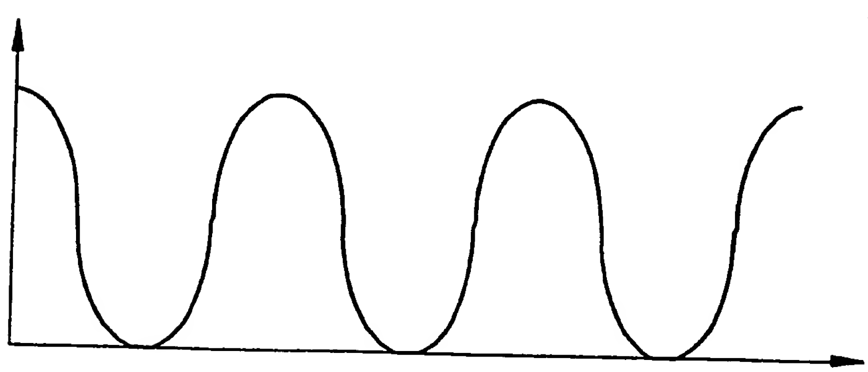

FIG.5C

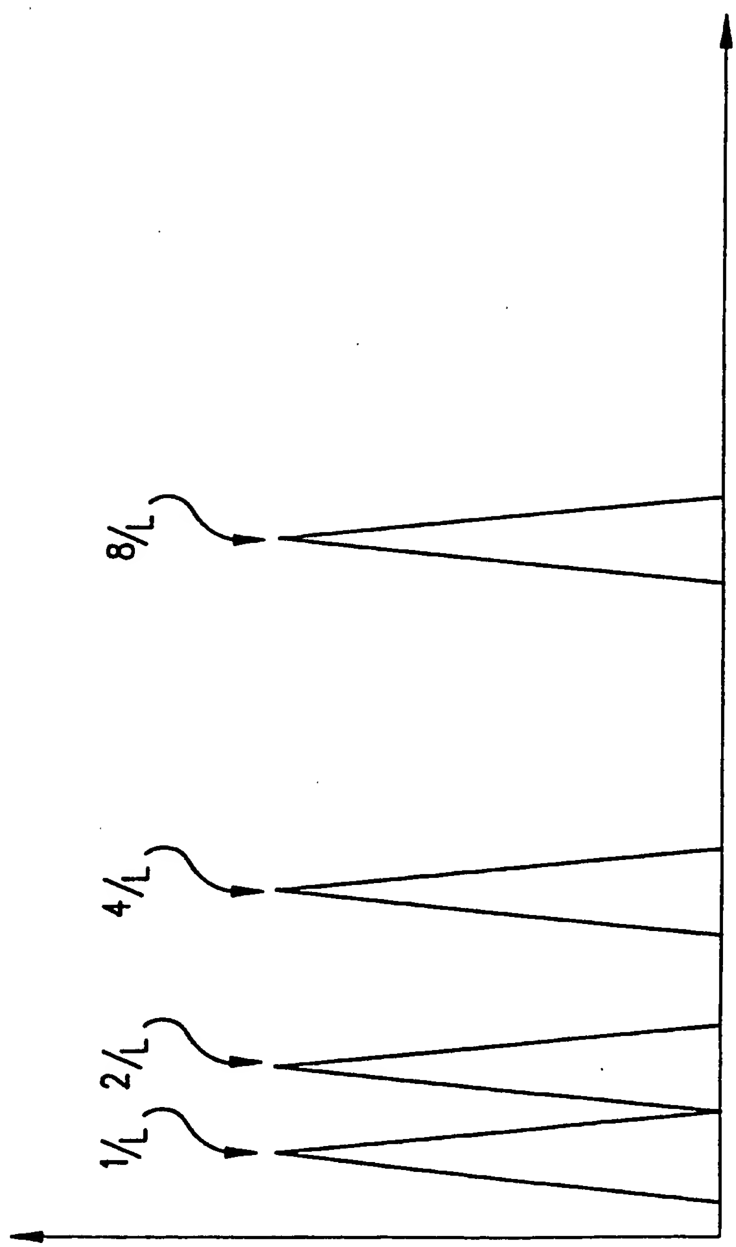

FIG.6

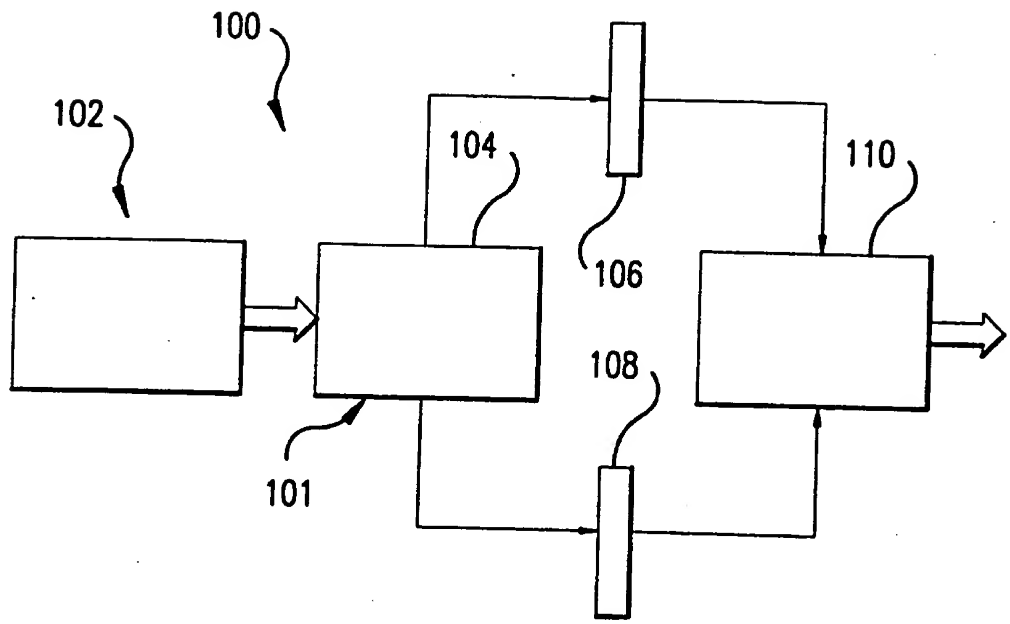

FIG.7A

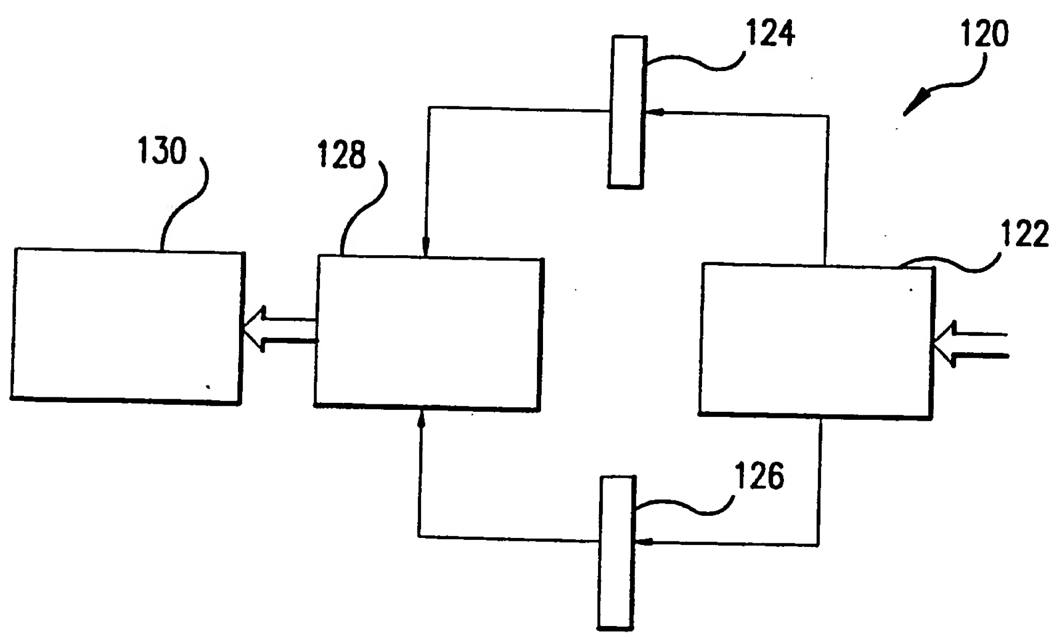

FIG.7B

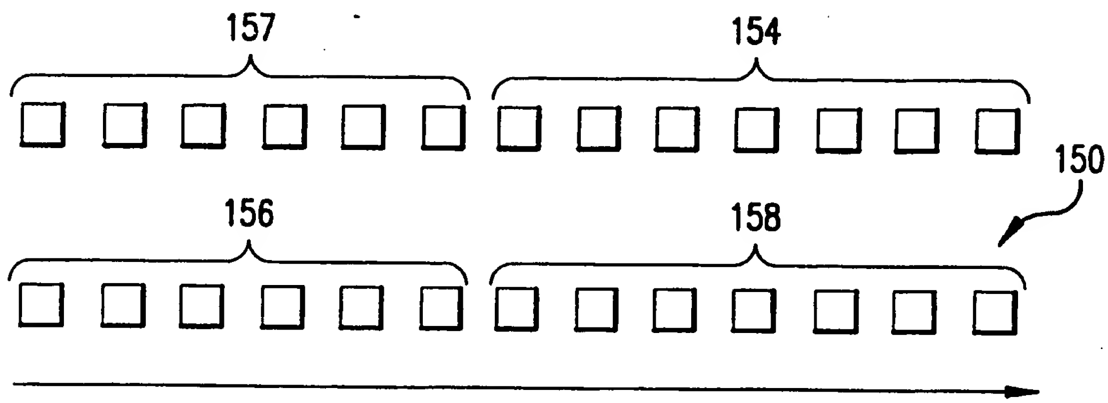

FIG.8A

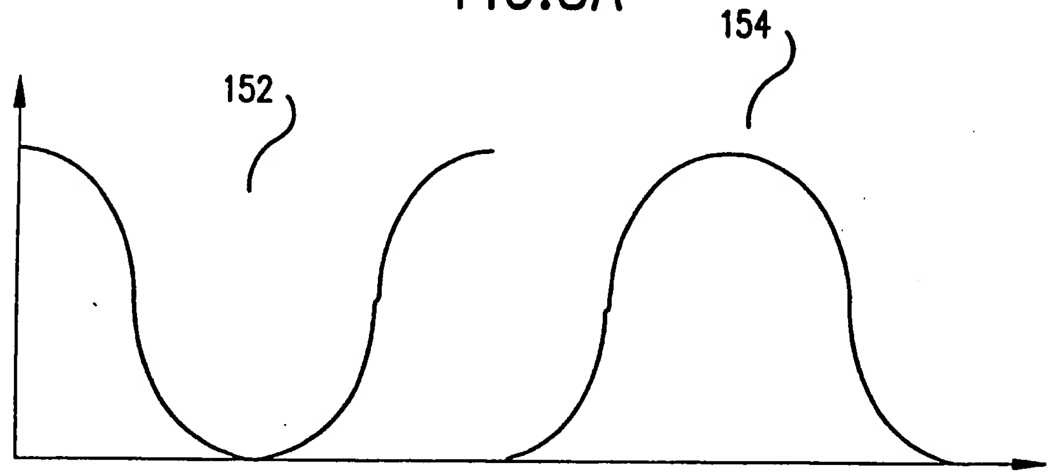

FIG.8B

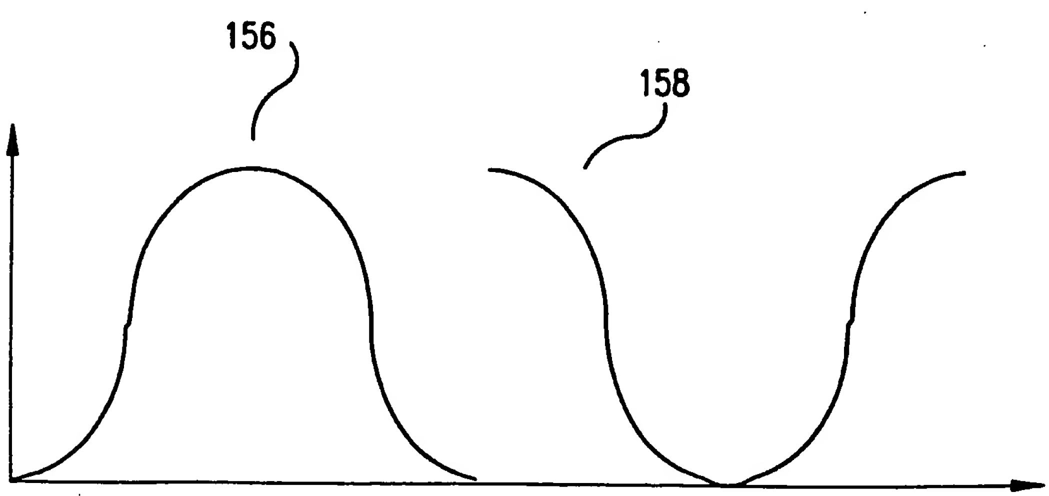

FIG.8C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/14120

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04J13/00 H04J14/02 G01J3/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04J H04B H04Q H01S G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HASSAN A A ET AL: "SPATIAL OPTICAL CDMA" IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, vol. 13, no. 3, 1 April 1995, pages 609-613, XP000497893	12,13,22
Y	see page 609, right-hand column, paragraph 1 - paragraph 3	19
A	see figures 1,2	1,5,15, 21,22

Y	US 3 873 825 A (JONES ROBERT PATRICK ET AL) 25 March 1975 see column 10, line 20 - line 23 see column 10, line 32 - line 49	19
A	see column 11, line 1 - line 37; figure 1	1,2,12, 22

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
28 November 1997	08/12/1997

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Pieper, T

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WEINER A M ET AL: "PROGRAMMABLE FEMTOSECOND PULSE SHAPING BY USE OF A MULTIELEMENT LIQUID-CRYSTAL PHASE MODULATOR" OPTICS LETTERS, vol. 15, no. 6, 15 March 1990, pages 326-328, XP000113554 see abstract see page 326, right-hand column, paragraph 2 - page 327, left-hand column, paragraph 2 ---	1,2,6, 12,13, 19,22
A	KAVEHRAD M ET AL: "OPTICAL CODE-DIVISION-MULTIPLEXED SYSTEMS BASED ON SPECTRAL ENCODING OF NONCOHERENT SOURCES" JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 13, no. 3, 1 March 1995, pages 534-545, XP000509320 see abstract see page 534, right-hand column, last paragraph - page 535, left-hand column, paragraph 2 see page 537, right-hand column, paragraph 1 see page 538, right-hand column, last paragraph - left-hand column, paragraph 1 see figures 1,2 ---	1,2,5, 12,15, 19,22
A	WEFERS M M ET AL: "PROGRAMMABLE PHASE AND AMPLITUDE FEMTOSECOND PULSE SHAPING" OPTICS LETTERS, vol. 18, no. 23, 1 December 1993, pages 2032-2034, XP000413235 see page 2032, left-hand column, paragraph 2 see page 2032, left-hand column, last paragraph - right-hand column, paragraph 11; figure 1 ---	1,5,12, 15,19
X	EP 0 031 027 A (IBM DEUTSCHLAND ;IBM (US)) 1 July 1981 see page 2, line 15 - line 35 see page 10, line 12 - line 33 see page 11, line 20 - page 13, line 9	24
A	see figure 3 ---	1,5,12, 15,19,22

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/14120

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	DECUSATIS C ET AL: "Hybrid optical implementation of discrete wavelet transforms: a tutorial" OPTICS AND LASER TECHNOLOGY, vol. 28, no. 2, March 1996, page 51-58 XP004026141 see abstract see page 54, left-hand column, paragraph 4 - page 55, left-hand column, paragraph 1	7,9, 12-18
A	WO 96 10163 A (BRITISH TECH GROUP ;BELTON PETER STANLEY (GB); WRIGHT KEVIN MICHAE) 4 April 1996 see page 1, line 30 - page 2, line 21 see page 2, line 28 - page 3, line 2 see page 7, line 21 - page 8, line 10 see figure 1	1-3,10, 12,13, 19-22

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 97/14120

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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EP 0031027 A	01-07-81	DE 2952071 A	24-09-81
		JP 56094227 A	30-07-81
WO 9610163 A	04-04-96	AU 3571895 A	19-04-96
		EP 0783671 A	16-07-97